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STUDIES FOR STUDENTS

RESULTS OF TESTS OF WISCONSIN BUILDING STONE III[1]

In this the concluding paper on the testing of building stones I will summarize and discuss various tests which I made in the laboratory of the Wisconsin Geological Survey during the winter of 1897–8.

In examining the tests recorded in some of the reports on building stones I found them to be really of little value, either on account of the failure of the operator to describe carefully the methods employed in making the tests or owing to insufficient care in manipulation and computation. It has been noted that among sedimentary rocks the results of tests on samples from different parts of the same quarry may be very different. Such differences may be even more marked than those that occur between samples from different quarries within the same area. It is possible to select samples from a quarry which will give very high tests, while a greater part of the stone may be of the poorest kind. Valuable results can only be obtained when tests are made upon samples which are a fair average of the stone as it occurs in the quarry.

For making the tests herein discussed, the author endeavored to obtain samples which represented as nearly as possible average No. 1 stone. The tests were performed as nearly as possible in accordance with the instructions laid down in the previous paper. The utmost care was exercised in obtaining truthful results, and it is believed that the figures given are nearly accurate for the samples tested.

[1] The illustrations accompanying this paper are used by permission of the director of the Wisconsin Geological and Natural History Survey. A fuller discussion of these tests will be found in Bulletin No. IV of the Wisconsin Geological and Natural History Survey reports.

CRUSHING STRENGTH

The individual test which is employed perhaps more than any other to determine the strength and durability of a stone is the crushing strength test. For years certain architects and builders have relied upon this test almost exclusively for forming an estimate of the suitability of a stone for all kinds of public and private buildings. This general use of the crushing strength test is still prevalent in some sections of the country.

In order to be assured of the reliability of the machine in which the crushing strength tests were to be made, comparisons were made with tests made in two other machines on samples from the same quarries. One of the machines used was also calibrated to give positive assurance of its reliability. In making the tests, note was taken of the position of the sample in the machine with respect to bedding or schistosity.

Twenty-seven samples of granite from twelve different quarries were tested. The lowest crushing strength obtained was 12,704 pounds per square inch, while the highest was 47,674 pounds per square inch. The average crushing strength of all the samples tested was 27,023.7 pounds per square inch. The minimum crushing strength was above the maximum crushing strength obtained for sandstone, and was obtained on a sample of granite gneiss in which the lamination was diagonal to the direction of the pressure. As far as my knowledge extends the maximum crushing strength is the highest yet recorded for any rock tested in the United States. It was obtained from a sample of rhyolite on which the pressure was applied normal to the head or in the direction of the rift.

It has been generally supposed that the crushing strength of a stone is least in the direction of the rift or lamination, but apparently this is not true in the case of the rhyolite in question. This rhyolite consists of elongated crystals of feldspar and other minerals in a very dense groundmass, forming what one might consider a very compact bundle of fibers. A rock with such a structure can apparently sustain a greater pressure when applied in the direction of these fibers than when applied across them.

Further, a careful examination of the polished faces of this rock shows that the feldspar crystals are broken by numerous cross fractures. These small, scarcely perceptible fractures may account in part for the less load which the rock is capable of sustaining normal to the rift. The cone which remained after crushing this sample of rhyolite is shown in Plate I.

The highest crushing strength obtained for true granite was 43,973 pounds per square inch, which was obtained on a sample of the Montello stone. This, so far as my knowledge goes, is the highest crushing strength that has been recorded for any United States granite. It exceeds the highest test on the Fourche Mountain granite[1] of Arkansas by nearly 15,000 pounds per square inch, while the highest test on the granite from St. Cloud,[2] Minn., is 16,000 pounds less than this. The granite from Redgranite, Waushara county, also gave a crushing strength of over 36,000 pounds per square inch, which exceeds the highest test made on the Fourche Mountain granite by 7000 pounds per square inch. These illustrations give evidence that in at least three different areas in Wisconsin granite and rhyolite occur, which, as far as known, surpass in strength granite or rhyolite from any other quarry in the United States.

Most of the granite samples broke with an explosion. Ordinarily an upper pyramid or cone, such as shown in the accompanying illustration, Plate I, was all that remained after the test. In a few cases a lower or opposite pyramid remained, but as a rule this part of the sample was reduced to powder. In many of the cones that remained a concentric structure had been developed through the pressure, which had much the appearance of cleavage. This is nicely shown in the accompanying illustration, Plate II.

Thirty-one tests were made on limestone from eleven different quarries. The strongest sample tested gave a crushing strength of 42,787 pounds per square inch, which is about 18,000 pounds higher than any known test recorded for limestone,

[1] Annual Report Arkansas Geological Survey, 1890, Vol. II, p. 42.

[2] Geological and Natural History Survey of Minnesota, 1884, Vol. I, p. 196.

dolomite, or marble in the United States. The stone which gave this test was a thoroughly crystalline, well compacted, and homogenous dolomite. The weakest sample tested gave a crushing strength of a little over 6600 pounds per square inch. The strength of the weakest limestone is very little less than that of the ordinary sandstones tested. The sample which gave the highest test was from the Marblehead Lime and Stone Company's quarry in the Niagara formation. Other samples from the Niagara formation gave tests of 39,983 pounds, 36,731 pounds, 33,485 pounds, 32,171 pounds, and 31,800 pounds per square inch.

The crushing of the samples of limestone was ordinarily accompanied with less noise than the granite. Occasionally the samples scaled off along the edges and corners before the maximum load was applied. In some cases two pyramids were developed, but as a rule, only one remained after crushing the more perfectly prepared cubes. The pyramids resulting from the crushing of limestone are ordinarily much steeper and more slender than those of the granite. Occasionally wedge-like forms were developed which resembled the wedge-shaped pyramids of the granite, as shown in Plate II, Fig. 2 and Plate IV, Fig. 3. Occasionally the samples are reduced to splinters, even the pyramids falling in pieces when raised from the steel plate. The cone which remained after the "record sample" of limestone was crushed is shown in Plate III, Fig. 6. Other typical pyramids resulting from crushing limestone samples are shown in Plate III, Figs. 1–5.

The crushing strength was determined for forty-five samples of sandstone from eleven different quarries. The samples from several of the quarries were thoroughly indurated while others were very soft and incoherent. In most cases the cementing material was silica but in some of the weaker samples iron oxide was the principal bonding constituent. Compared with the strength of the granite and limestone, the sandstone may be considered relatively weak. The sample which gave the highest strength test was from the quarry of the Chicago and

Northwestern Railway Company at Ablemans. This sample gave a test of 13,431 pounds per square inch. The lowest test was 1658 pounds per square inch, made on a sample of Lake Superior brown sandstone tested on edge. The lowest test across the bed was 2502 pounds made on a sample of Dunnville sandstone. The average strength of all the sandstone samples tested, one half of which were on edge and the other half on the bed, was 6361 pounds per square inch. The average crushing strength of twenty tests of the Lake Superior brown sandstone, one half of which were on edge and the other half on the bed, was 4618 pounds per square inch. This is a somewhat higher average crushing strength than that recorded for the Bedford öolitic limestone of Indiana.[1]

The weaker the sandstone and the more uniform the grains, the more perfect are the pyramids which develop. In the stronger samples the pyramidal form is replaced by the conical. In the samples of moderate strength almost perfect pyramids form on both the upper and lower sides, as shown in the accompanying illustration, Plate IV, Figs. 1 and 4.

In performing these tests my attention was called to the fact that the crushing strength on edge of the weakest samples was considerably less than that on the bed, while in the stronger rocks the difference was much less. The compressive strength of several different limestones was higher when the pressure was applied along the bed than when applied across it. The Berlin rhyolite, which is the strongest stone tested, gave the highest strength test when the pressure was applied in the direction of easiest parting. These results indicate that there are exceptions to the general rule that a stone will withstand the greatest pressure when applied normal to the bed. Apparently the rule applies only to stone which has a low compressive strength. When the compressive strength is very high the opposite result is fully as likely to occur and may even prove the rule.

The manner in which the cubes of stone break indicates to a greater or less extent the strength of the stone. Crushing a

[1] Twenty-first Annual Report of the Indiana Department of Geology and Natural Resources, p. 317.

stone which has a compressive strength of less than 10,000 pounds per square inch usually results in the formation of two quite well defined pyramids. The pyramids resulting from crushing a stone with a compressive strength of between 10,000 and 20,000 pounds per square inch are ordinarily less perfect. The pyramids resulting from testing stone of this class are frequently wedge-shaped but more often they are intermediate between a pyramid and a cone. The crushing of cubes having a compressive strength of over 30,000 pounds per square inch usually results in the formation of only one pyramid which has more of a conical than pyramidal outline.

In crushing the granite and also some of the limestone and sandstone cubes a concentric structure was developed similar to that illustrated in Plate II, Figs. 4, 5, and 6.

TABLE I.

CRUSHING STRENGTH[1]

Ultimate Strength in Pounds per Square Inch.

	Highest test	Lowest test	Average
Granite and rhyolite: twenty-seven samples from twelve different quarries..............	47,674	12,704	27,023.7
Limestone: thirty-one samples from eleven different quarries..........................	42,787	6,675	25,312.8
Sandstone: forty-five samples from eleven different quarries......	13,699	1,658	6,125.0

TRANSVERSE STRENGTH

The determination of the modulus of rupture is of as great if not greater importance than the crushing strength. As previously indicated, it is especially valuable in determining the required thickness of a stone which is intended to be supported at the ends, and which carries a heavy weight of superstructure in the middle.

The modulus of rupture was determined for only two Wisconsin granites. The results in each case were over 2300 pounds

[1] For detailed results of individual tests see Bulletin No. IV, Wisconsin Geological and Natural History Survey, "Building and Ornamental Stones," 1898.

per square inch. The average transverse strength of the Montello granite was over 3780 pounds per square inch. The samples broke suddenly, and the fracture extended diagonally across the center of the pieces.

The modulus of rupture was determined for samples of limestone from eight different quarries. The results ranged from 1164.3 pounds to 4659.2 pounds per square inch. The highest result obtained was on a sample of stone from the Laurea Stone Company's quarry at Sturgeon Bay. The stone from the Marblehead Lime and Stone Company's quarry at Eden gave a modulus of rupture of 3632 pounds per square inch. All of the transverse strength tests were high. The samples broke very close to the center and much quieter than the granite.

The modulus of rupture was determined for sandstone from six different quarries. The results ranged from 362.9 pounds to 1324 pounds per square inch. The highest test obtained was on samples from the Chicago & Northwestern Railway Company's quarry at Ablemans. Eight tests of the brown sandstone from the Lake Superior region gave an average modulus of rupture of about 500 pounds per square inch.

A comparative examination of the results shows that the finely crystalline limestone possesses a higher modulus of rupture than either the sandstone or granite. However, it is ordinarily less rigid than either of these stones, and is more liable to sag when suspended at the ends.

TABLE II

TRANSVERSE STRENGTH

Modulus of Rupture in Pounds per Square Inch

	Highest test	Lowest test	Average
Granite and rhyolite: four samples from two different quarries	3,909.7	2,324.3	3,156.2
Limestone: ten samples from eight different quarries	4,659.2	1,164.3	2,761.15
Sandstone: sixteen samples from six different quarries	1,324	150.2	558.8

MODULUS OF ELASTICITY

Up to the present time very few determinations of the modulus of elasticity have been made, especially in the United States. However, a knowledge of the modulus of elasticity is of value to architects and builders in many of their calculations.

The modulus of elasticity was determined for granite from eleven different quarries. The results varied between wide limits, ranging all the way from 156,000 pounds to 2,070,000 pounds per square inch. The first result is comparatively low, while the latter is very high. Four samples of granite from Wausau gave tests of from 1,040,000 to 1,815,000 pounds per square inch. The Athelstane granite from Amberg tested very close to 1,000,000 pounds per square inch. The Pike River gray granite from the same place tested nearly 1,500,000 pounds per square inch.

The modulus of elasticity was determined for limestone from four different quarries. The results obtained varied from 31,500 pounds per square inch to 869,400 pounds per square inch. The highest result was obtained for limestone from the Washington Stone Company's quarry which is located at Sturgeon Bay.

The modulus of elasticity was determined for samples of sandstone from ten different quarries. The results of these tests varied from 32,000 pounds to 400,800 pounds per square inch. The highest result was obtained for samples of white sandstone from the Chicago & Northwestern Railway Company's quarry at Ablemans. The modulus of elasticity of the Lake Superior brown sandstone ranged from 56,000 to 387,900 pounds per square inch.

In general it will be noted that the modulus of elasticity corresponds approximately with the crushing and transverse strength of the different rocks tested. The crushing strength, transverse strength, and modulus of elasticity were all lower for the sandstone samples tested than for either the limestone or granite.

TABLE III

MODULUS OF ELASTICITY

In Pounds per Square Inch

	Highest test	Lowest test	Average
Granite and rhyolite: twenty-one samples from eleven different quarries	2,070,000	156,000	1,068,634
Limestone: eleven samples from five different quarries	1,835,700	31,500	786,145
Sandstone: twenty-eight samples from ten different quarries	400,800	32,000	163,861

HARDNESS

The hardness of a stone can be easily determined with the abrading machine known as the Deval.[1] For making this test a definite quantity (5 kg) of cubical pieces of stone from two to two and one half inches in diameter are placed in one of the cylinders of this machine, which is then rotated for five hours at a rate of about thirty-three revolutions per minute. The percentage of dust which is worn off by this treatment is the measure of the hardness of the stone. The coefficient of wear, which is another and the usual method of expressing the hardness, is computed from the following formula:

$$Q = \frac{20 \times 20}{W},$$

in which

Q = the coefficient of wear
W = the quantity of dust formed.

Two samples of granite from each of two quarries were tested in the abrading machine, with the results given in Table IV. Quartzite from one quarry, trap rock from one quarry, and limestone from seven quarries were also tested, with the results given in Table IV.

TABLE IV

HARDNESS OR COEFFICIENT OF WEAR

	Highest	Lowest	Average
Granite: four samples from two quarries	4.88	3.54	4.14
Trap: two samples from one quarry	3.03	2.07	2.55
Quartzite: two samples from one quarry	2.70	2.28	2.49
Limestone: fourteen samples from seven quarries	2.22	0.79	1.51

[1] For description of this machine see the Report of the Massachusetts Highway Commission for 1899, pp. 59, 60.

SPECIFIC GRAVITY

The weight of a rock per cubic foot will increase with the specific gravity proper and decrease with the percentage of pore space. As indicated in a previous paper, the average specific gravity of the mineral constituents is taken as the specific gravity proper of the rock. Following this conception the pore spaces are not considered a part of the rock mass.

Twenty-five determinations of specific gravity were made on samples of granite from fourteen different quarries. The maximum specific gravity obtained was 2.713 and the minimum 2.629, while the average of all determinations was 2.655. Tests on twenty-two samples of limestone from eleven different quarries gave an average specific gravity of 2.806. The maximum specific gravity was 2.856 and the minimum 2.700. Tests on thirty-two samples of sandstone from sixteen different quarries gave an average specific gravity of 2.618. The maximum specific gravity was 2.660 and the minimum 2.524.[1]

In the case of the sandstone it is to be observed that the iron oxide which constitutes a part of the cement of the brown sandstone is not present in sufficient quantity to appreciably affect the specific gravity. The specific gravity of the granite, however, is influenced appreciably by the abundance of the ferro-magnesium minerals, as exemplified in the case of the Athelstane granite from Amberg, which gave the highest specific gravity test. An admixture of quartzose material naturally lowers the specific gravity of limestone.

The stone which gave the highest specific gravity was a very compact and finely crystalline dolomite, and it is interesting to note that samples from this same quarry gave the highest crushing and transverse strength of any of the limestone or dolomite tested.

WEIGHT PER CUBIC FOOT

Determinations of the weight per cubic foot were made for twenty-five samples of granite from fourteen different quarries.

[1] It is thought that this low specific gravity is due to an unknown error in manipulation.

The average weight per cubic foot according to these determinations was 163.29 pounds. All of the granites tested weighed within five pounds per cubic foot of one another.

The average weight of twenty-two limestone samples from eleven different quarries was 166.70 pounds per cubic foot. The maximum weight was 176.69 pounds per cubic foot and the minimum 148.50 pounds per cubic foot. The average weight of thirty-two samples of sandstone from sixteen different quarries was 136.36 pounds per cubic foot. The maximum weight was 153.63 pounds per cubic foot and the minimum 115.55 pounds per cubic foot.

POROSITY AND RATIO OF ABSORPTION

As has been previously pointed out, the porosity gives the volume relation between the pores and the mass of the stone, while the ratio of absorption gives the weight relation. None of the granites tested had a porosity of more than 1 per cent., while the porosity of most of the samples was about .45 of 1 per cent. Owing to the interlocking character of the grains, the pores of a granite are much smaller than those of arenaceous limestone or sandstone. The water is therefore taken up and given off very slowly. The ratio of absorption of the granite samples tested was nearly the same as the porosity.

The limestone samples gave porosities ranging from 13.36 per cent. to .14 of 1 per cent. The sample having a porosity of 13.36 per cent. had a ratio of absorption of about 5.6 per cent. The samples from the Marblehead Lime and Stone Company's quarry, which gave the high crushing and transverse strength tests, had a porosity of about .70 of 1 per cent.

The porosity of the sandstone samples ranged from 4.81 per cent. to 28.28 per cent. The average porosity of the brown sandstone samples was between 19 and 20 per cent. In the case of the samples of sandstone having a porosity of 28.28 per cent. the ratio of absorption was 15.22 per cent. The Lake Superior brown sandstones gave an average ratio of absorption of less than 10 per cent.

The walls of a building constructed out of a porous stone are seldom completely saturated with water, although they may be wetted by the water of imbibition which adheres as a film to the individual grains and is thus conducted through the body of the wall. If a stone with pores of capillary size should be saturated in any part with water and the supply be discontinued the interstatial water would be very quickly drawn off at the surface or at the base of the wall through capillarity. It rarely happens that atmospheric conditions are such that a stone with capillary pores can become saturated with water and freeze before the water is sufficiently dissipated to prevent injury.

Rocks in which the grains are closely compacted, without respect to size, will have a small percentage of pore space and also pores of very small size. Many of the pore spaces of the granite and limestone are certainly of not greater than sub-capillary size. Water is taken up and given off by a rock having pores of this size much more slowly than by one in which the pores are of capillary dimensions. When the sub-capillary pores of a rock contain water in any quantity they should be theoretically filled. The sub-capillary pores near the exposed surface of a stone wall may be filled by long-continued rains, although the water may never penetrate to any considerable depth. If such a period of weather is followed by freezing conditions a stone in which the pores are of sub-capillary size will be in greater danger than one having pores of capillary size. It should be remembered that stone is damaged by freezing only when the pores are over nine tenths filled with water.

A wall built out of granite or other stone in which the porosity may be very low, but the pores of sub-capillary size, is in as great danger from alternate freezing and thawing as a wall built out of sandstone or other rock in which the porosity is 15 or 18 per cent., but in which the pores are of capillary size. It must be understood that this does not apply to laminated, bedded, or shaly stone, between the layers of which the water may collect more rapidly than it can be carried off through the pores. Water which is thus collected along bedding or other parting

planes cannot be considered under the head of interstatial water, although it is a very prominent cause for the disintegration of building stone.

TABLE V

	Specific gravity	Porosity	Ratio of absorption	Weight per cubic foot
Granite:				
Maximum	2.713	.55	.500	169.05
Minimum	2.629	.019	.04	163.29
Average	2.655	.329	.158	164.98
Limestone:				
Maximum	2.856	13.36	5.60	176.69
Minimum	2.700	.53	.19	148.50
Average	2.806	4.89	1.946	166.70
Sandstone:				
Maximum	2.660	28.28	15.22	153.63
Minimum	2.524	4.81	2.00	115.55
Average	2.622	15.89	7.486	136.36

FREEZING AND THAWING TESTS

As said in a previous paper, the difficulties involved in manipulation and the many conditions which must be considered before conclusions can be drawn from quantitative results of freezing and thawing tests, have apparently had the effect of almost excluding these determinations from reports on building stones. The effect of alternate freezing and thawing may be manifested in three ways: (1) cracks may form; (2) small particles or grains may be thrown off from the surface, occasioning a loss in weight; (3) the cement may be weakened or the grains broken, causing the strength to be materially lessened.

Cracks.—Cracking, as a result of freezing, is seldom observed in the laboratory tests, owing to the careful manner in which the samples are usually prepared.

Loss in weight.—Small particles are frequently shoved off from the surface of a sample which is subjected to alternate freezing and thawing. Where incipient joints occur small flakes are also sometimes loosened by pressure of the freezing water. Many of the grains at or near the surface of sandstone samples become loosened in the process of sawing or hammer dressing. These grains usually adhere to the sample so loosely that they

fall away from the parent mass under very moderate pressure. Loose particles at the surface are naturally more plentiful in the case of sedimentary rocks such as sandstone than they are in the case of igneous rocks or finely crystalline limestone. The loss in weight due to alternate freezing and thawing *will depend mainly* upon the manner in which the samples have been dressed and the kind of stone tested. The experiments which I have performed have demonstrated to my satisfaction that alternate freezing and thawing for a period of thirty-five days results in scarcely more than the removal of the loosened grains or fragments from the surface. Any loss in weight which may be partly accounted for by the manner of preparing the samples does not indicate the extent to which the stone has been injured.

Loss in weight due to freezing and thawing was determined for eighteen samples of granite from eleven different quarries. The loss in weight in these cases did not exceed .05 of 1 per cent. on a mass of about 350 to 360 grams. In the case of limestone, in which twenty-one samples from eleven different quarries were tested, the loss did not exceed .3 of 1 per cent., being, as a rule, less than .1 of 1 per cent. The loss in weight of the sandstone samples, of which twenty-four from twelve different quarries were tested, did not exceed .62 of 1 per cent. and averaged about .28 of 1 per cent.

TABLE VI

FREEZING AND THAWING TESTS

Loss per cent. of weight

	Highest test	Lowest test	Average
Granite and rhyolite: sixteen samples from eleven different quarries	.05	.006	.035
Limestone: twenty-one samples from eleven different quarries	.30	.005	.0753
Sandstone: twenty-four samples from twelve different quarries	.62	.015	.276

Such losses in weight are almost insignificant, and are valuable mainly in showing that the more loosely compacted

sandstone samples have more of the exterior grains loosened in preparation than do the granite, rhyolite, and limestone. It is very probable that had these same samples been subjected to a second period of alternate freezing and thawing, the granite, limestone, and sandstone would have agreed more nearly in the loss by weight.

Loss in crushing strength.—The result of alternate freezing and thawing is more clearly manifested by a decrease in the crushing strength of the rock than by the loss in weight. It is very evident that if a stone having sub-capillary pores is subjected to alternate freezing and thawing for a considerable period, the adhesion of the particles will be weakened and the cement perhaps shattered or broken. This will not necessarily occasion an immediate loss in weight, but must necessarily decrease the strength of the stone. The samples which were subjected to alternate freezing and thawing for thirty-five days were broken in a testing machine to determine their crushing strength. The crushing strength thus obtained was compared with the crushing strength obtained from the samples of fresh stone. With a few explainable exceptions, the crushing strength of the frozen samples of granite was much less than that of the fresh. The crushing strength of the frozen samples from ten different granite quarries was less than the crushing strength of the fresh samples by from 2201 pounds to 13,075 pounds per square inch. In the case of limestone samples from eleven different quarries the frozen samples from eight showed a loss in crushing strength of from 571 pounds to 18,714 pounds per square inch. Among the frozen samples of sandstone from ten different quarries, six gave crushing strength tests which ranged from 326 to 6264 pounds per square inch lower than the crushing strength of the fresh samples. The average loss for all the frozen samples of each kind of rock is given in Table VII. Table VIII gives a comparison between the average crushing strength of fresh and frozen samples, and also the average loss through freezing.

TABLE VII

ULTIMATE STRENGTH IN POUNDS PER SQUARE INCH OF FROZEN SAMPLES

	Highest test	Lowest test	Average
Granite and rhyolite: sixteen samples from twelve different quarries	37,027	9,765	22,875
Limestone: twenty-one samples from eleven different quarries	34,784	5,584	18,267
Sandstone: twenty-four samples from twelve different quarries	9,245	2,116	4,724

TABLE VIII

COMPARATIVE CRUSHING STRENGTH OF FRESH AND FROZEN SAMPLES

	Crushing strength of fresh samples	Crushing strength of frozen samples	Difference, or loss in strength through freezing
Granite and rhyolite: average difference in strength of twenty-three fresh and eighteen frozen samples from eleven different quarries	29,696	22,793	6,903
Limestone: average difference in strength of twenty-one fresh and twenty-one frozen samples from eleven different quarries	25,222	18,267	6,955
Sandstone: average difference in strength of eighteen fresh and twenty-four frozen samples from ten different quarries	5,461	4,453	1,008

These experiments illustrate two points which I have made in the previous discussion: (1) that the results of freezing and thawing can be best estimated from the loss in crushing strength; (2) that the larger the pores, without respect to the percentage of pore space, the less will be the injury from freezing and thawing. There is little doubt but that a stone having a high percentage of pore space, *if completely saturated* with water and frozen, will suffer greater injury than one with a lower percentage. But the conditions under which freezing takes place must be considered before conclusions reached are of any practical value. These conditions include a time element which enters to modify very materially the results. After making this time element as short as the conditions under which the experiments

were performed would permit, it was demonstrated that the strength of the sandstone, which had a high percentage of pore space, was less affected by freezing and thawing than the strong granites and limestones having a low percentage of pore space. It was naturally thought that the Dunnville sandstone, which has 28.28 per cent. of pore space, and consists of relatively fine particles, would experience a greater loss in strength than any of the other rocks tested. The results, however, give evidence that a rock as fine-grained and poorly-cemented as this, with pore spaces which are little greater than sub-capillary size, is but slightly injured by alternate freezing and thawing.

It has been a matter of frequent observation that limestone and marble suffer more by hard freezing immediately after being taken from the quarry than other stones which have a higher porosity. This has usually been spoken of as exceptional, but I venture to say that between limestone, marble, and sandstone, the two former can furnish more examples of injury by freezing of interstatial water than the latter. A reasonable explanation for this result would be that the pore spaces in the limestone are usually of sub-capillary size, while those in the sandstone are mainly of capillary size.

EFFECTS OF SULPHUROUS ACID GAS

Limestone, dolomite, and marble are the only stones which are to any extent injured by sulphurous acid gas. Eleven samples of limestone and dolomite from as many different quarries were exposed for forty-four days to sulphurous acid gas in a moist atmosphere. Some of the pieces of limestone were colored yellow, others were slightly etched on the surface, while many of the samples showed a glistening precipitate of magnesium salts. By washing the samples the magnesium salt was taken into solution and through this the weight of the sample was slightly decreased.

The deterioration of limestone or dolomite in a moist atmosphere laden with sulphurous acid gas is apparently not very rapid. Where deterioration does not proceed very rapidly under

such extreme conditions, in an ordinary atmosphere it would be many years before the gas would have any appreciable effect upon the limestone in the walls of a building.

EFFECT OF CARBONIC ACID GAS

Eleven samples of limestone and dolomite were tested to determine the effects of carbonic acid gas in a moist atmosphere. After treatment for forty-four days there was apparently no deterioration either in weight or color.

EFFECT OF HIGH TEMPERATURE

Few experiments have thus far been performed to determine the limit of temperature which different kinds of stone will stand without injury.[1] It is known, however, that a stone will stand a much higher temperature when heated and cooled slowly than when heated and cooled rapidly.

Samples of granite from six different quarries were tested in a muffle furnace to determine the temperature which they would stand without being destroyed. The samples were all practically uninjured up to a temperature of 1200° F. but most of them were destroyed before a temperature of 1500° F. was reached. Eleven different samples of limestone from as many different quarries were tested and each of them was partially calcined before a temperature of 1400° F. was reached. The eleven samples of sandstone which were tested were mostly destroyed at a temperature of less than 1200° F. although in one instance a temperature of 1500° F. apparently left the sample uninjured.

All the heated samples when struck with a hammer or scratched with a nail emitted a sound very similar to that given off by brick. Planes of lamination were brought out more distinctly as the temperature increased.

The samples of granite cracked differently depending upon whether they were coarse or fine grained. The very coarse grained granite samples broke in a great many places and may be said to have exploded. The cracks were so numerous in one

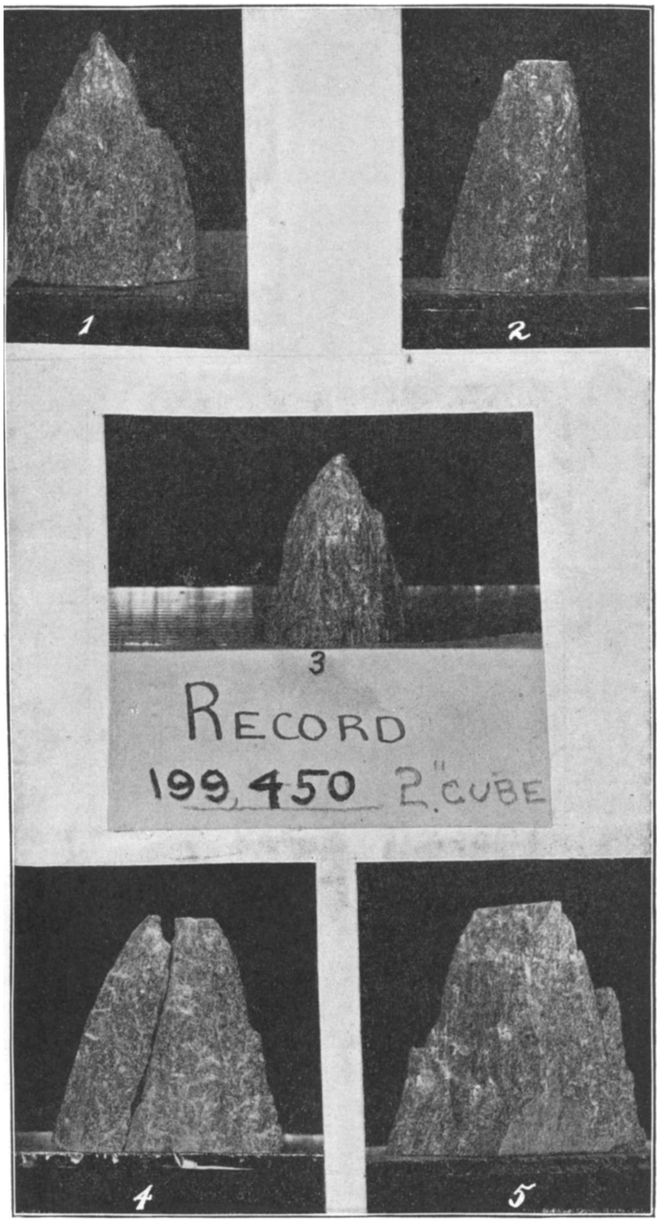
[1] See "Notes on Building Stones" by HIRAM CUTTING, Montpelier, Vt., 1880.

EXPLANATION OF PLATE I

RESULTS OF CRUSHING GRANITE AND RHYOLITE

The figures in this plate illustrate some of the more perfect cones resulting from crushing the stronger samples of granite and rhyolite. Fig. 1 is a typical result for granite of this class, while Fig. 3 is a typical rhyolite cone. This latter cone resulted from crushing a two-inch cube of granite, which gave a test of nearly 48,000 pounds per square inch. It will be further observed that Figs. 4 and 5 have wedge-shaped apices similar to those illustrated in Pl. IV, Fig. 3.

JOUR. GEOL., VOL. VIII, NO. 6 Plate I



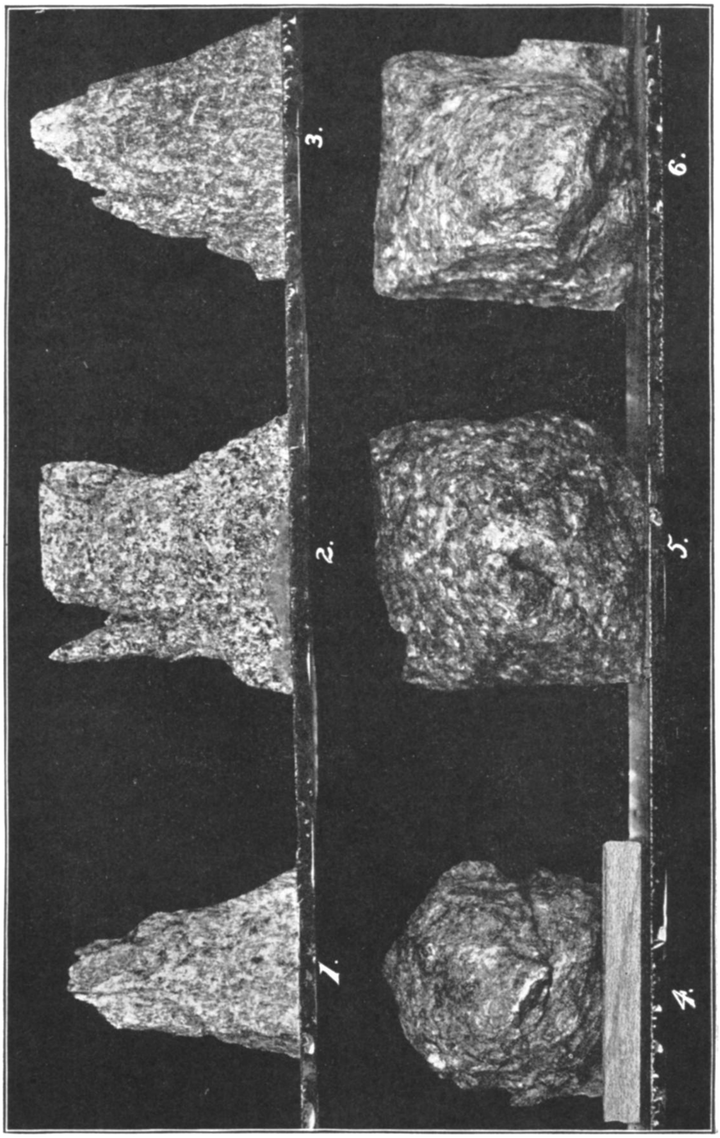
Results of crushing granite and rhyolite cubes.

EXPLANATION OF PLATE II

FIGS. 1, 2, and 3.—These samples illustrate the different forms developed in crushing granite cubes. The one on the left is a typical cone. The one on the right has a tendency toward the wedge-shaped form, while the one in the middle is a typical wedge form. The upper part of this wedge is a sharp ridge from one end to the other.

FIGS. 4, 5, and 6.—These three figures have their apices pointing toward the observer. They are all well shaped cones, in which there has been especially well developed the concentric structure referred to in the text.

JOUR. GEOL., VOL. VIII, NO. 6 Plate II

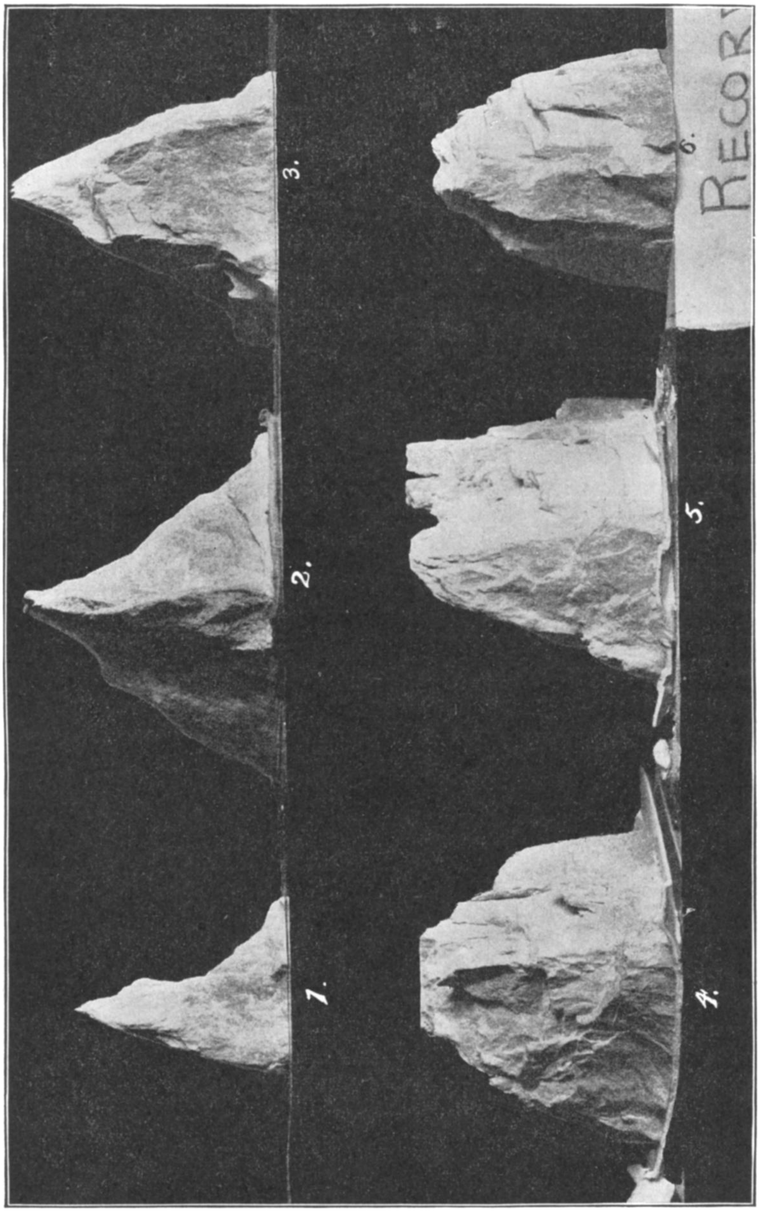


Results of crushing granite cubes.

EXPLANATION OF PLATE III

The figures in this plate illustrate the results of crushing samples of the strongest limestone of Wisconsin. The sample in the lower right hand corner, Fig. 6, gave a crushing strength test of 42,787 pounds per square inch, which is thought to be the highest record obtained for any limestone, dolomite, or marble quarried in the United States. This sample shows, near the apex of the somewhat irregular cone, the concentric cleavage structure, which is typically developed in the granite.

JOUR. GEOL., VOL. VIII, No. 6 Plate III



Results of crushing limestone cubes.

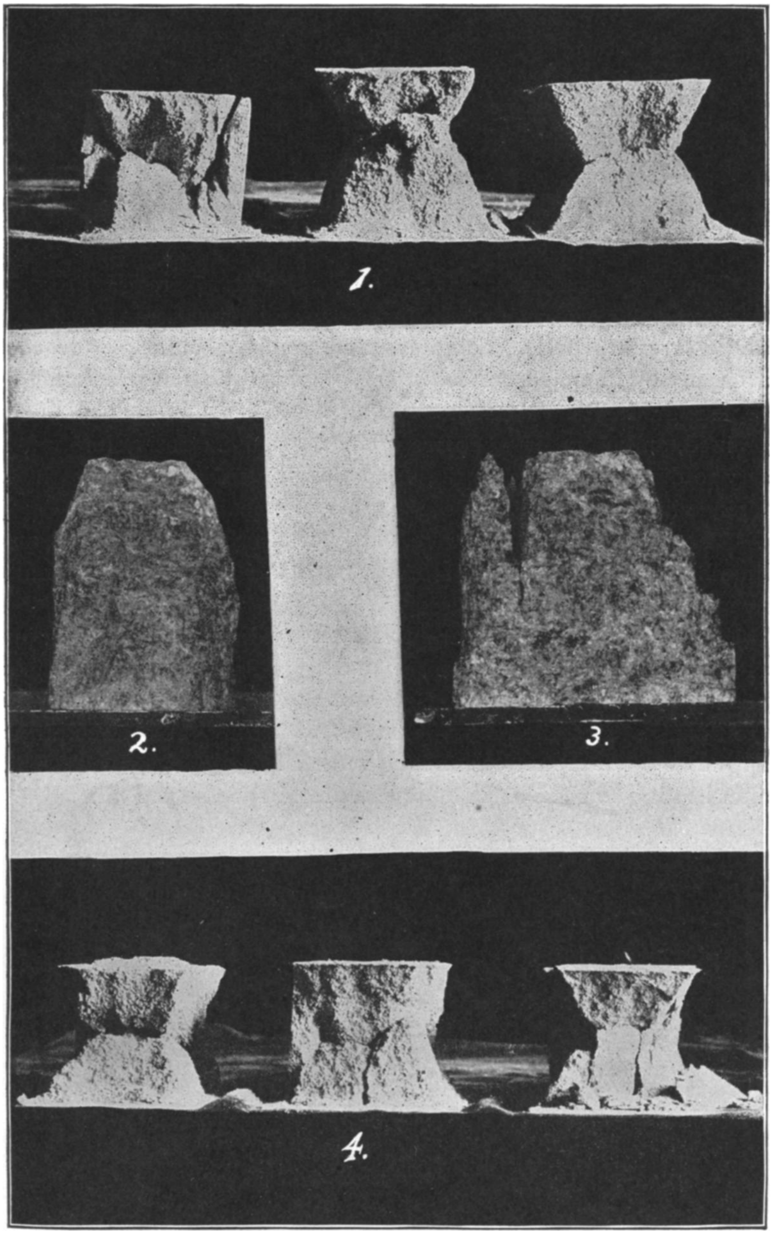
EXPLANATION OF PLATE IV

FIG. 1.—Samples of brown sandstone in which the pyramidal forms are well developed.

FIGS. 2 and 3.—Samples of granite. Only the upper wedge or pyramid was developed in each cube. Fig. 2 approaches the conical form, which ordinarily results from crushing granite. (See Pl. II.) Fig. 3 is the typical wedge-shaped form, which often results from crushing granite of medium strength.

FIG. 4.—Samples of brown sandstone in which the pyramidal structure is well developed. These are typical results obtained from crushing sandstone of ordinary strength. It should be observed that the samples which have a low or medium crushing strength are the only ones in which two equally well developed pyramids occur.

JOUR. GEOL., VOL. VIII, NO. 6 Plate IV



Results of crushing sandstone and granite cubes.

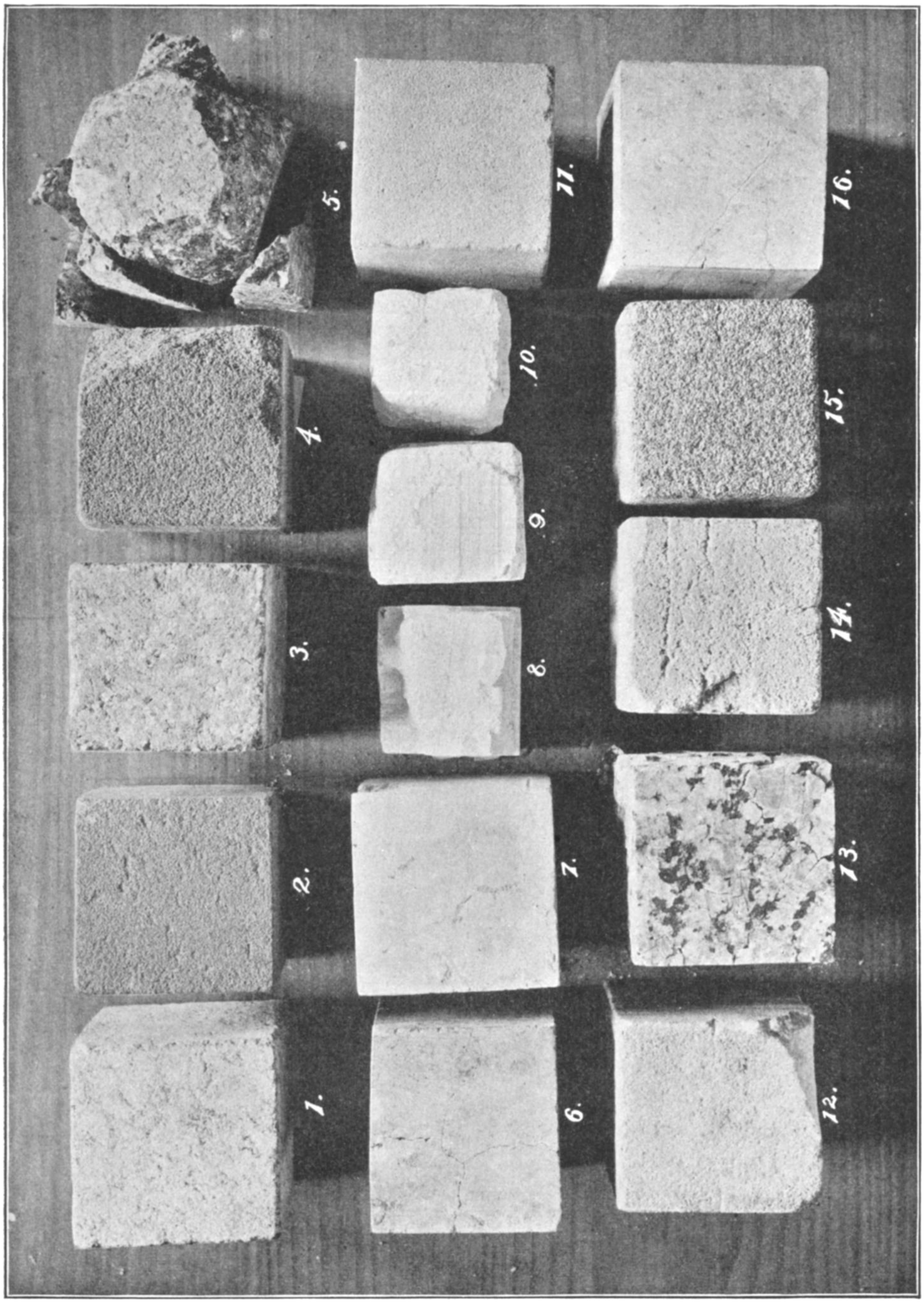
EXPLANATION OF PLATE V

The samples numbered 1, 3, 6, 7, 13, and 16 are granite; those numbered 8, 9, 10, and 11 are limestone; and numbers 2, 3, 4, 12, 14, and 15 are sandstone. Samples numbered 5, 6, and 13 were cooled suddenly by immersing them in cold water, while the remaining were cooled gradually. Number 6 is fine grained, number 5 medium grained, and number 13 coarse grained granite. It is simply necessary to direct attention to these samples, for one to see how the difference in grain influenced the manner of cracking.

The limestone samples were partly calcinated. Where the quicklime has been removed the samples have the rounded edges noticed in numbers 9 and 10.

The sandstone samples are, to all outward appearances, uninjured, as shown in samples numbered 2 and 15. The chipping of the corners and edges in numbers 4, 12, and 14 was occasioned by pressing the thumb against the parts broken off, which in spite of the uninjured appearance of the samples, indicates the friable character of the stone after heating to the extreme temperature of 1300°–1500° F.

JOUR. GEOL., VOL. VIII, NO. 6 Plate V



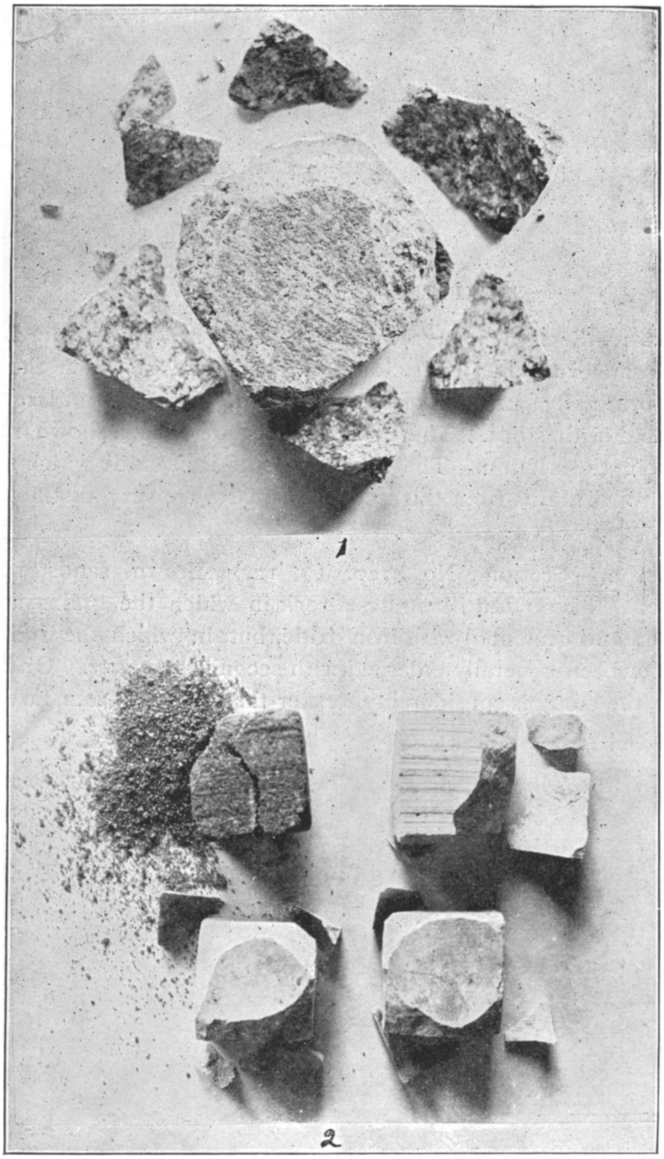
Results of subjecting different kinds of stone to high temperatures.

EXPLANATION OF PLATE VI

FIG. 1.—A sample of medium-grained granite heated to a temperature of from 1300°–1500° F., and suddenly cooled by immersing in cold water. This figure is a good illustration of the result of throwing a stream of water on the walls of a burning building, which is con structed out of granite of this texture.

FIG. 2—The sample in the upper left hand corner is sandstone which has become so friable by being heated to a temperature of 1300°–1500° F., that it crumbles when pressed between the fingers. The remaining samples are limestone. They have flaked off at the corners, due to having been quickly cooled from a very high temperature. Such results may frequently be noticed in the limestone walls of buildings which have been destroyed by fire.

JOUR. GEOL., VOL. VIII, NO. 6 Plate VI



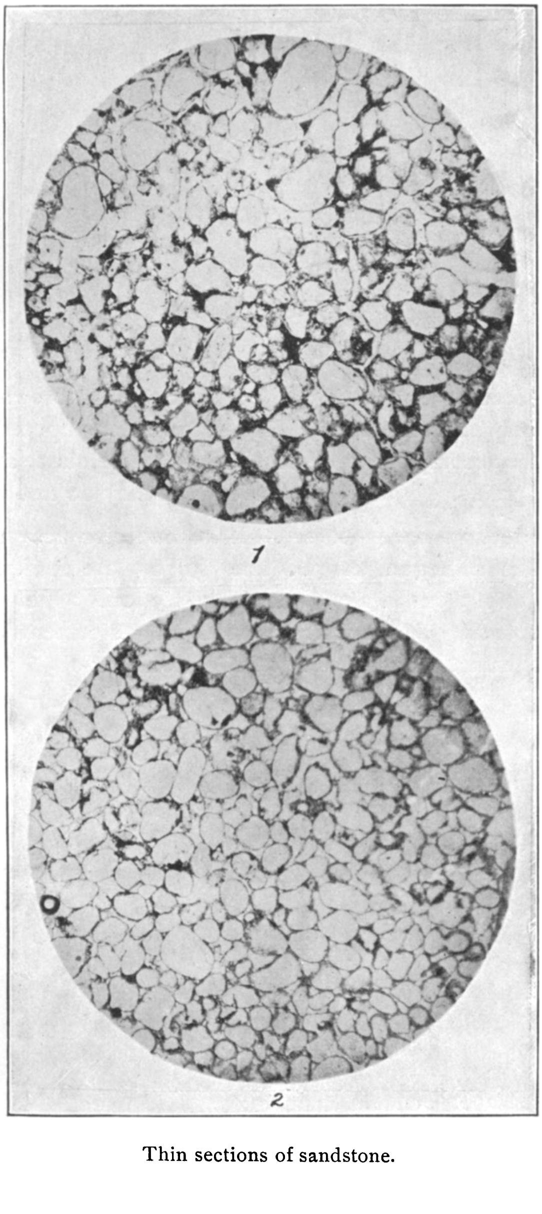
Results of rapidly cooling samples of granite, limestone, and sandstone that have been heated to a high temperature.

EXPLANATION OF PLATE VII

FIG. 1.—Section No. 4721. ($\times$ 12.)[1] Red sandstone from LaValle. This is an excellent illustration of a sandstone in which the grains were originally uniformly well rounded, and later enlarged and cemented with silica. The enlargements are nicely shown in many places in the section. The brown rims of iron oxide which separate the original grains from the secondary quartz are very distinct in the figure.

FIG. 2.—Section No. 4720. ($\times$ 12.) Brown sandstone from Argyle. This section illustrates a rock in which the grains are well-rounded and cemented with iron oxide, but in which the individuals have not been generally enlarged with secondary quartz. On account of this the stone is considerably weaker than the one from LaValle.

[1] Magnified twelve diameters.

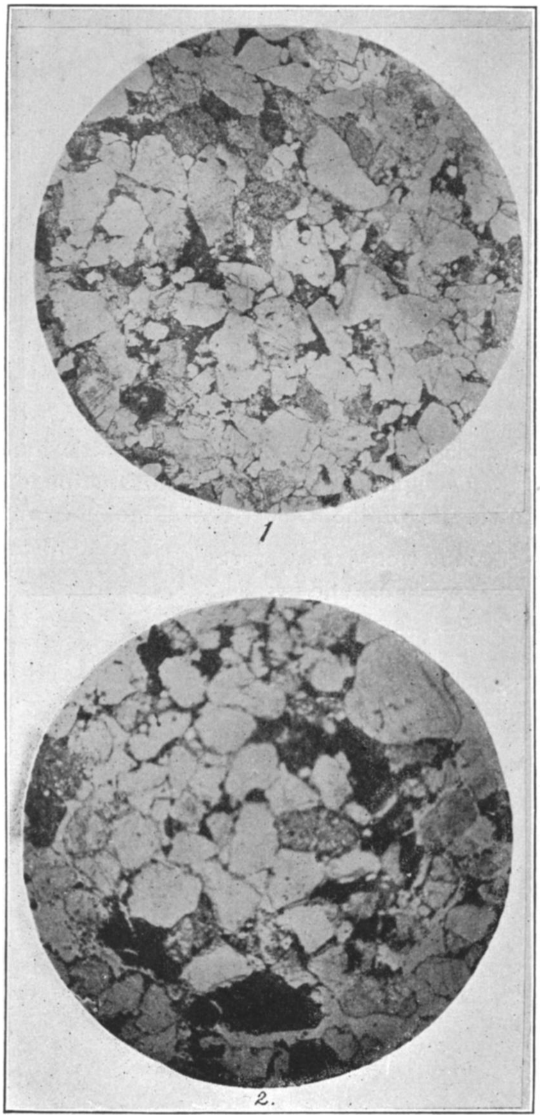


Thin sections of sandstone.

EXPLANATION OF PLATE VIII

FIG. 1.—Section 4719 (× 12). Lake Superior brown sandstone from the Chequamegon Area. This section is composed mainly of quartz and the accompanying figure shows the size, shape and arrangement of the grains. It will be observed that they do not interlock.

FIG. 2.—Section 4714 (× 12). Lake Superior brown sandstone from the Chequamegon Area. The grains are somewhat better rounded in this, than in the preceding section. One will quickly notice the secondary quartz which in many places cements the individual grains together. Occasional grains of feldspar occur among those of quartz.



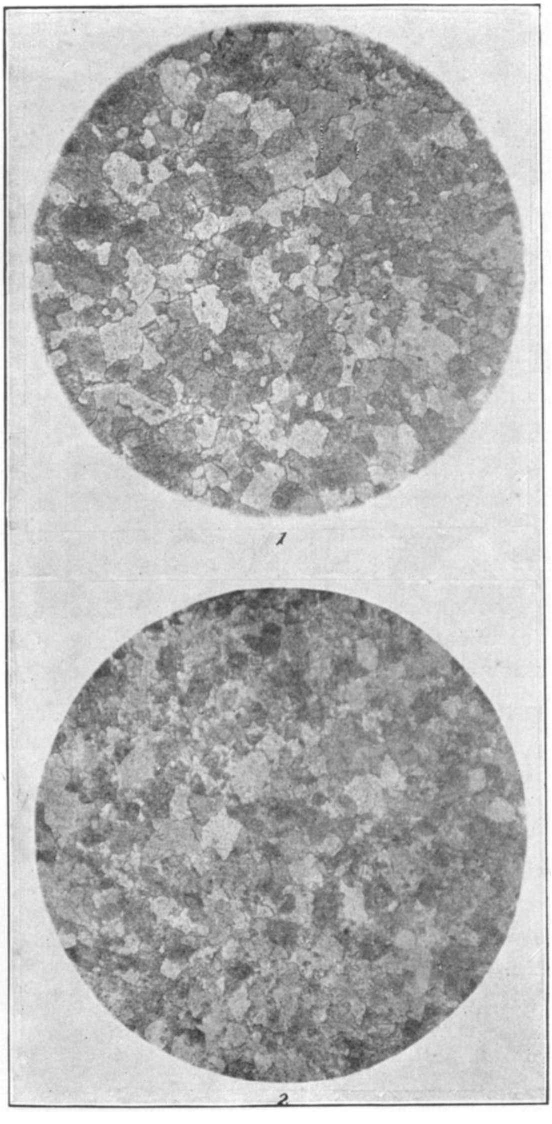
Thin sections of sandstone.

EXPLANATION OF PLATE IX

FIG. 1.— Section No. 4736. (× 12.) Dolomitic limestone from Duck Creek. This figure is an excellent illustration of the way in which the individuals of the coarser crystalline limestones interlock.

FIG. 2.— Section No. 4726. (× 12.) Dolomitic limestone from Sturgeon Bay. This figure shows the close, compact character of the crystalline dolomites, which accounts for their low percentage of pore space, and partly for their high crushing strength.

Jour. Geol., Vol. VIII, No. 6 Plate IX



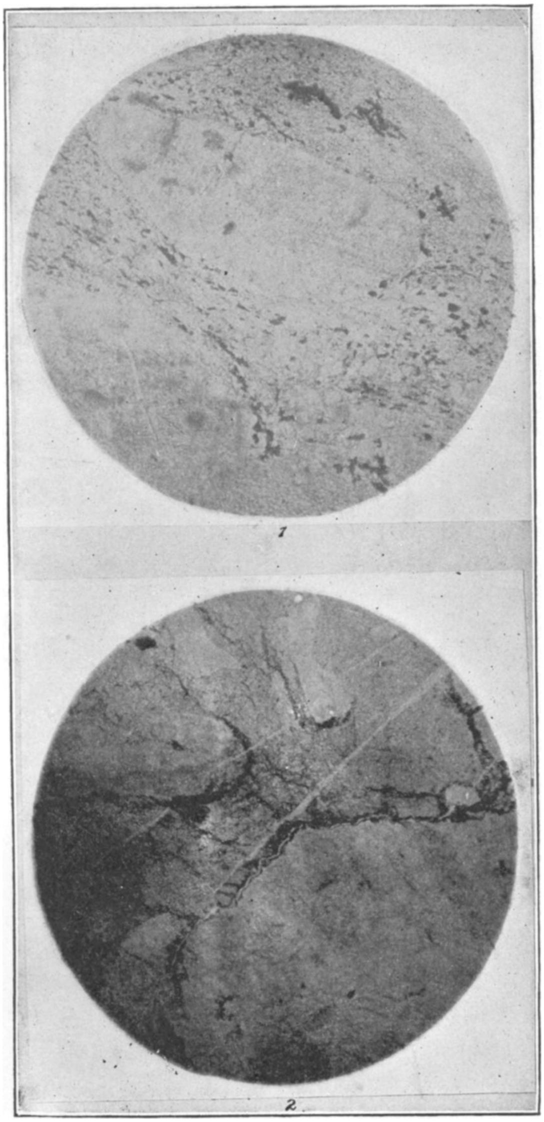
Thin sections of limestone.

EXPLANATION OF PLATE X

FIG. 1.—Section No. 4733. (× 12.) Berlin rhyolite. This figure shows the exceedingly fine grained matrix and the porphyritic individuals of feldspar, which are characteristic of the rock in the hand specimen. The mica which occurs in small flakes is also nicely shown. The parallel arrangement of the small flakes, which is evidently a cause for the "rift" in the rock, is well brought out. The cracking of the feldspar, referred to in the text, is also seen in this figure.

FIG. 2.—Section No. 4704. (× 12.) Utley rhyolite. Porphyritic crystals of quartz and feldspar and a small portion of the fine, dense matrix are shown in this figure. The compactness of the rock, with the consequently minute pores and low porosity are very evident.

JOUR. GEOL., VOL. VIII, NO. 6 Plate X



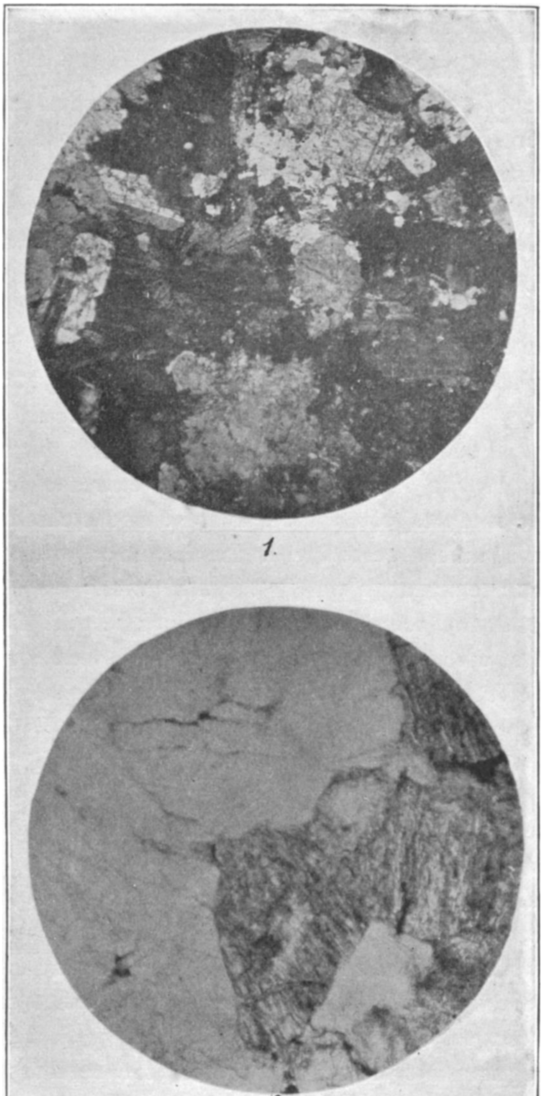
Thin sections of rhyolite.

EXPLANATION OF PLATE XI

FIG. 1.—Section No. 4702 (× 12). Granite from Waupaca. This rock contains a greater variety of minerals than No. 4711. Besides quartz and feldspar there is an abundance of chlorite, epidote, and, in some places, biotite. The individuals are interlocking, but less regular than in many granites.

FIG. 2.—Section No. 4711 (× 12). Granite from Granite Heights. The dark colored parts are feldspar, and the lighter colored are quartz. This section illustrates nicely the close, interlocking character of the different individuals which contributes largely to the strength of the rock.

JOUR. GEOL., VOL. VIII, NO. 6 Plate XI



Thin sections of granite.

of the samples that it broke into fragments not much larger than the individual grains. The granites having medium sized grains flaked off at the corners when cooled moderately fast. The fine grained granite, such as the Montello, developed cracks through the middle of the sample. The different ways in which the granites were cracked and broken are illustrated in Plate V.

In contrast with the limestone and granite, the sandstone was to all appearances little injured by the extreme heat. Samples which were taken from the muffle furnace and allowed to cool gradually appeared to be uninjured, but after they had cooled one could crumble any of them in the hand almost as easily as he could the most incoherent sandstone. In fact, some of the samples when heated to a temperature of 1500° F. became so incoherent that after they had cooled they could scarcely be picked up without falling into sand. A person might be easily deceived as to the injury occasioned by extreme heat on sandstone. The samples often look as fresh and clean as when first quarried and, unless tested with the hammer, one would never suspect that the strength was so largely gone.

In general, the temperature tests indicate that there are few if any stones, whether they be granite, limestone, or sandstone, which will effectually withstand for a moderate length of time a temperature of 1500° F.

MICROSCOPIC TESTS

Thin sections of the more important building stones which were otherwise inspected were examined under a compound microscope. The microscopic examination reveals clearly the texture, composition and finer structures of the rock. These, combined with the field observations, furnish abundant data from which a person familiar with microscopical studies can estimate both the strength and durability of a stone.

The irregular interlocking character of the grains composing the igneous and finely crystalline rocks give evidence of strength which far exceeds that displayed by the sandstones composed of rounded grains which are held together by occasional patches of

ferruginous or siliceous cement. Each sample by itself has peculiarities in texture and composition which either add or detract from the strength and durability of the stone.

Plates VII, VIII, IX, X, and XI, with the accompanying explanations, illustrate the character of several of the Wisconsin building stones and the elements which contribute to their strength and durability.

E. R. Buckley.